

Beam Steering by Lag Synchronization in Ultra-Wide Bandwidth, Chaotic Arrays

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Abstract. We introduce a new method for beam steering in ultra-wide bandwidth arrays. The approach avoids the need for tunable microwave delays by using lag synchronization in a linear array of locally coupled chaotic oscillators. Steering is controlled by tuning the natural frequency of the oscillators and is analytically equivalent to first order to using explicit delay elements. Using chaotic rf circuits oscillating at ~ 20 MHz, we show both lag and lead synchronization can be practically controlled in rf arrays.

1. INTRODUCTION

Recently, nonlinear chaotic oscillators have been suggested as efficient sources for generating ultra-wideband radar waveforms. The broadband and non-repeating nature of chaos provides an ideal combination of high range resolution with no range ambiguity. Unlike standard noise waveforms, chaotic waveforms are generated by simple deterministic oscillators, which allow for easy control (Ott et al., 1990) and synchronization (Pecora and Carroll, 1990). For ultra-wideband radar, it is natural to consider the power combining properties of arrays of chaotic microwave oscillators (Corron et al., 2003). Local coupling can synchronize an extended array, thereby providing a coherent state suitable for beam forming in a wide-bandwidth radar system.

The ability to electronically steer a beam is critical for a practical system. As depicted in Fig. 1, wideband steering requires a true time delay between radiating elements. Following conventional phased array design, a wideband array requires a tunable delay for each element, which is economically impractical with current microwave technology. Alternatively, we propose to use synchronization due to local coupling in a chaotic array. To steer the array, a small detuning is applied to each oscillator to slightly shift its natural frequency. Oscillators that are tuned to run faster will lead those tuned slower, providing a small time shift between the waveforms produced by each oscillator. This effect is called lag synchronization, which has recently been observed and reported for mismatched chaotic systems (Rosenblum, 1997). Similar ideas have been proposed for narrowband arrays (Meadows et al., 2002); however, application of lag synchronization to chaotic arrays is new, and we recently reported the first experimental results using an array of three rf oscillators (Corron et al., 2004).

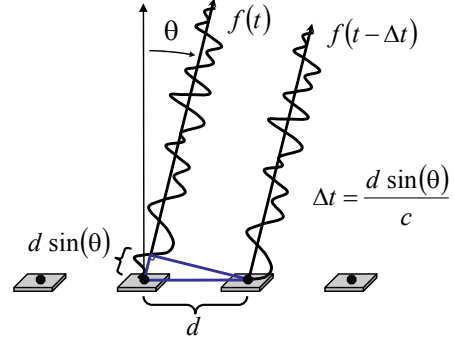


Fig. 1. Beam Steering in a wide bandwidth array.

2. NOVEL RF CHAOS CIRCUIT

To explore lag synchronization, we developed a new 20-MHz chaotic oscillator, shown in Fig. 2. This simple circuit requires just one active component—a negative resistor—and a nonlinear device consisting of two diodes. The negative resistor is implemented using a fast voltage-feedback operational amplifier (Texas Instruments OPA690). A typical waveform generated by this circuit is shown in Fig. 3.

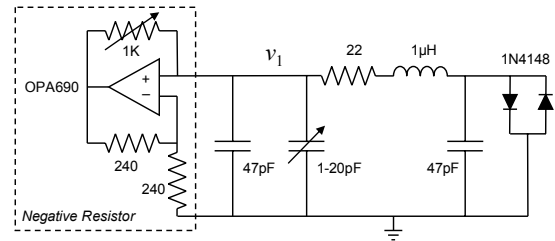


Fig. 2. 20-MHz chaotic oscillator.

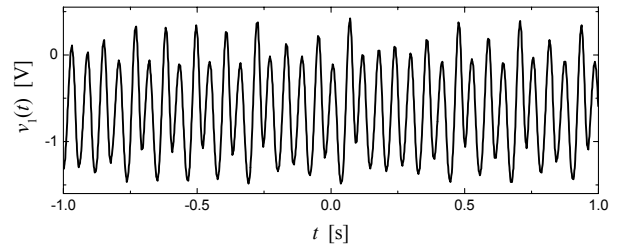


Fig. 3. Typical waveform from chaotic circuit.

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3. OSCILLATOR ARRAY

Multiple chaotic oscillators can synchronize using unidirectional coupling as shown in Fig. 4. Here, the left oscillator (drive) is coupled unidirectionally to the right oscillator (response) via a unity gain buffer and a resistor R_S . To make a larger array, additional response circuits are coupled to the right as indicated, creating a chain of unidirectionally coupled oscillators.

We control lag synchronization in the array by tuning a capacitor $C(\tau)$ in each response oscillator. For $C(\tau) = C_1$, the response will synchronize identically with the drive. Increasing $C(\tau) > C_1$ by the same small amount in all response oscillators results in a consistent time delay τ between array elements. Experimental results for a 3-element array using $R_S = 510 \Omega$ are shown in Fig. 5. This method for inducing lag synchronization is analytically equivalent to first order in τ to using explicit delay elements, and a significant lag can be induced by increasing $C(\tau)$ as much as 10%. Experimentally, the induced lag is controlled continuously to more than 5 ns, or about 1/10th of a cycle. Generally, the lag increases with $C(\tau)$, but we observe a gradual degradation in synchronization quality for larger lag. Eventually, synchronization is lost for large $C(\tau)$, as the response circuits lose phase lock with the drive and the array is no longer coherent.

We also observed a range of lead or anticipating synchronization (Voss, 2000), corresponding to a negative delay. Experimental observation of anticipating synchronization in chaotic rf systems has not previously been reported. This state is achieved by decreasing $C(\tau) < C_1$, yielding response states that lead the drive. Experimental results are shown in Fig. 6. Similar to lag synchronization, the quality of lead synchronization degrades smoothly up to a critical detuning, where phase locking is suddenly lost. However, the range of high-quality lead synchronization is significantly less than that of lag synchronization, which we attribute to fundamental limitations of anticipating synchronization (Pethel et al., 2003).

4. CONCLUSIONS

We developed a new method to control a true time delay using lag synchronization and demonstrated the mechanics of beam steering in a 3-element rf array. This approach is analytically equivalent to first order to using variable delay lines, but is much simpler and more economical to implement. As a result, chaotic microwave arrays may soon enable a new generation of low-cost, high-performance, ultra-wide bandwidth radar.

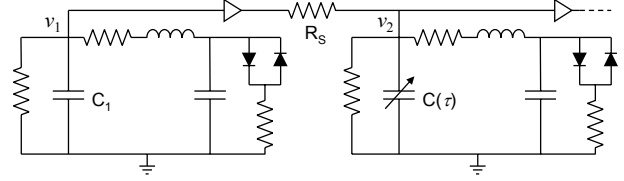


Fig. 4. Array with unidirectional local coupling.

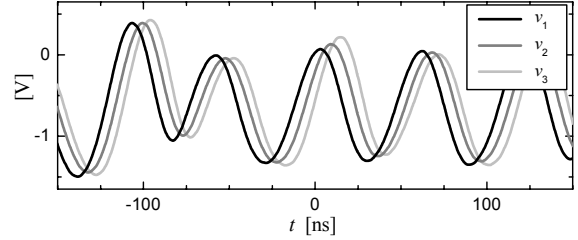


Fig. 5. Experimentally observed lag synchronization.

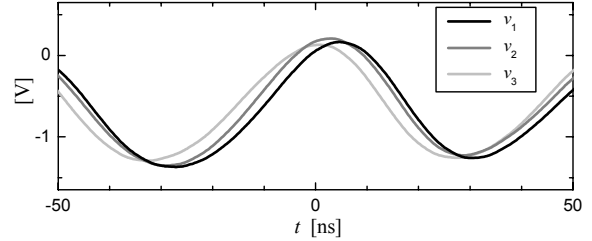


Fig. 6. Observed lead or anticipating synchronization.

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